

INVESTIGATION OF INTERPLANETARY DUST FROM
OUT-OF-ECLIPTIC SPACE PROBES

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ABSTRACT

Measurements of interplanetary dust via zodiacal light observations and direct detection are discussed for an out-of-ecliptic space probe. Particle fluxes and zodiacal light brightnesses are predicted for three models of the dust distribution. These models predict that most of the information will be obtained at space probe distances less than 1 A.U. from the ecliptic plane. Joint interpretation of the direct particle measurements and the zodiacal light data will yield the best knowledge of the three-dimensional particle dynamics, spatial distribution, and physical characteristics of the interplanetary dust. Such measurements are important for our understanding of the origin and role of the dust in relation to meteoroids, asteroids, and comets, as well as the interaction of the dust with solar forces.

Introduction

The microscopic dust particles are an important constituent of our solar system. A knowledge of the physical and dynamical properties of these dust particles in three dimensions should aid our understanding of the origin and evolution of the planetary system and furthermore of circumstellar dust clouds as detected by infrared astronomy. In this paper we discuss the type of dust measurements suitable for an out-of-ecliptic mission and the information which could be expected from these measurements.

The interplanetary dust can be explored from space probes by two complementary methods:

1. Direct detection of individual particles intercepted by a sensor. Velocity and mass parameters can be derived and, depending on the specific experiment, information on the chemical composition. Recent experiments have extended the limiting sensitivity down to masses of about 10^{-16} g at impact velocities of approximately 20 km/s (Hoffman et al. 1975).
2. Zodiacal light observations. Measurements of the brightness, color, and polarization of sunlight scattered by the dust particles give information on the average scattering properties and the spatial distribution of the dust along the line of sight (ref. Leinert 1975).

Direct detection has the advantage of defining a complete set of parameters for individual particles but the drawback of

sampling only a small number of particles. The zodiacal light observations sample a large volume of space, but the information on the physical properties of the particles is indirect.

Combined data from these two methods can be valuable especially if the direct detection instrument is sensitive enough to cover the entire mass range which may contribute to the zodiacal light. The combined data can in principle specify particle velocities, orbits, size, mass range, spatial distribution, and the general physical composition of the dust grains (structure, density etc.). These parameters are necessary for an understanding of the dynamical history of the dust particles, their relation to cometary and asteroidal material, and their interaction with it.

Extensive ground-based photometry and polarimetry of the zodiacal light has been carried out (see for example Weinberg 1964, Dumont and Sánchez 1975). However, observations from the earth alone have the fundamental drawback that the spatial distribution and the particle scattering function can not be uniquely separated, unless some assumptions are made about the decrease of particle number density with solar distance and about the independence of dust composition from the position in the solar system (Dumont and Sánchez 1975). Information about the validity of such assumptions can be obtained by zodiacal light photometry and polarimetry from space probes still in the ecliptic plane but far from the earth's orbit (Giese and Dziembowski 1969, Hanner and Leinert 1972).

The zodiacal light experiments on Pioneer 10/11 and Helios provide the brightness and polarization of the zodiacal light as a function of heliocentric distance in the ecliptic plane, (Manner et al. 1975, Link et al. 1975) from which the large-scale spatial distribution in the ecliptic between 0.3 and 3.3 A.U. can be derived.

Impact detectors with increasing sophistication have been used to measure particle fluxes and velocities by experiments on the space missions of Pioneer 8/9, Prospero, HEOS 2, Pioneer 10/11, and Helios (Berg et al. 1971, Bedford 1975, Dietzel et al. 1973, Hoffmann et al. 1975, Humes et al. 1974, Soberman et al. 1974). Pioneer 8/9 and submicron-sized impact craters on lunar surface samples showed the existence of a component of small particles moving outward from the sun under the influence of non-gravitational forces (Berg and Grün 1973, Fechtig et al. 1974).

The interplanetary dust forms a non-stable dust cloud in the solar system. The continuous sources are mainly comets, asteroids, and space erosion processes. It is, however, unknown which of these processes contribute to which extent. The main dust sink is, besides impacts on planets and their satellites, undoubtedly the sun: dust particles spiralling into the sun according to the Poynting-Robertson effect (Wyatt and Whipple 1950) presumably lead to a vaporisation near the sun (Sekanina 1975) and hence to a dust stream of submicron-sized remnants

leaving the solar system as a result of the radiation pressure force. These so-called beta meteoroids (Zook and Berg 1975; Zook, in press) are also produced by mutual collisions of meteoroids. Hemenway has suggested that a component of these beta meteoroids is being formed directly at and ejected by the sun (Hemenway et al 1972). In addition to these interplanetary particles, a component of interstellar origin can possibly be expected.

Models of Out-of-Ecliptic Dust Distribution

To predict the particle flux and the zodiacal light brightness which might be observed from an out-of-ecliptic probe, we chose three models for the spatial distribution of the dust, as described by Giese (1975).

$$\text{I} : n(r) = n_0 \cdot r^{-\gamma} \left(1 + (\gamma \sin \beta_0)^2 \right)^{-\gamma/2}; \gamma = 9.0 \text{ (Ellipsoid model)}$$

$$\text{II} : n(r) = n_0 \cdot r^{-\gamma} \exp \left[-(\gamma z)^2 \right]; \quad \gamma = 2.5 \text{ (Gauss model)}$$

$$\text{III} : n(r) = n_0 \cdot r^{-\gamma} \exp \left[-|\gamma \sin \beta_0| \right]; \quad \gamma = 3.0 \text{ (Fan model)}$$

Here $n(r)$ is the particle number density as a function of distance r (A.U.) from the sun, n_0 is the number density at 1 A.U. in the ecliptic plane, z (A.U.) is the distance above or below the ecliptic plane, and β_0 is the heliocentric ecliptic latitude

($\sin \beta_0 = z/r$). We have set the parameter $v = 1.0$, consistent with the Pioneer 10/11 and Helios zodiacal light data. The flattening parameter γ was adjusted for each model to give the ratio 0.32 for the brightness of the zodiacal light at the ecliptic pole to the brightness in the plane at elongation 90° , as observed by Dumont (1973).

Contours of equal dust density are illustrated in Figures 1a, 1b, and 1c respectively for the three examples. All three models predict that the dust is considerably concentrated toward the ecliptic plane. In comparison, the spatial distribution of radio meteors derived by Southworth and Sekanina (1973) shows a similar z -dependence at a x -distance of 1 A.U., but an increasing number density beyond 1 A.U. in the ecliptic plane.

The 0.5 contour in our examples ranges from $z = 0.2$ to 0.4 A.U. at $x = 1.0$ A.U.. The spatial density at 1 A.U. away from the ecliptic is at most $0.1 n_0$. Thus, observations of the zodiacal light and direct detection of particles will take place mainly at space probe distances less than 1 A.U. from the ecliptic.

Direct Detection

Direct measurements from an out-of-ecliptic mission could help to identify the various sources and sinks of the non-stable dust cloud. On the basis of the results of Pioneers 8/9 and HEOS 2

missions in the ecliptic at 1 A.U. and on the basis of the three models referred to above, the number of events per orbit were computed for a detector surface of 100 cm^2 and a space probe on a circular orbit of 1 A.U. radius having an ecliptic inclination of 30° or 60° or 90° respectively. Two cases of vehicle stabilisations (spinner with axis perpendicular to the orbital plane and three-axis stabilisation) were considered. The results are presented in Table 1 excluding or including the case of particles coming directly from the sun (marked 'no sun particles' or 'sun particles').

From these data it is evident that, while such a particle detection experiment is not able to differentiate among the various models of the spatial distribution directly, it could provide information on the role of the sun as a possible dust sink or source. Furthermore, the event rate is sufficient to continue analysis of enough individual particles to look for differences in composition between particles with low- and high-inclination orbits.

Zodiacal Light

The brightness and polarization of the zodiacal light can be predicted theoretically as a function of observing direction and observer's position in the solar system for any spatial distribution. If one assumes, that the average scattering properties of the particles are independent of location in the

solar system, then the brightness variation with spacecraft position is directly related to the spatial distribution of the dust (Hanner and Leinert 1972). Models for the zodiacal light distribution over the sky as seen from an out-of-ecliptic space probe were discussed by Giese (1971). By use of the same program we have computed for our three dust models the variation of zodiacal brightness for an out-of-ecliptic space probe on a circular orbit of 1 A.U. radius as a function of the z distance between the spaceprobe and the ecliptic plane. The maximum value z_m of z is related to orbital inclination i by $z_m = (1 \text{ A.U.}) \cdot \sin i$. For the scattering function a simple diffraction plus isotropic reflection form (albedo = 1) was chosen. The size distribution adopted was a 3-part power law $n(a)da \propto a^{-\kappa}$ with $\kappa = 2.7$; 2; or 4.33 in the regions of particle radii from 0.008 to 0.16; 0.16 to 29; or 29 to 189 μm , and $n_0 = 3.7 \cdot 10^{-13}$; $4.3 \cdot 10^{-15}$; or $7.4 \cdot 10^{-18}$ particles/ cm^3 in each regime, respectively. This is a fair approximation taking into account both the distribution of particle radii as derived by Grün (1975) from direct measurements (Fechtig et al. 1974), and the brightness of 200 stars of tenth magnitude per square degree ($200 S_{10}$) found by Dumont and Sánchez (1975) at $\epsilon = 90^\circ$ elongation in the ecliptic.

Figs. 2a through 2c present the decrease of zodiacal light brightness with increasing orbital altitude z of the probe for the three models of Fig. 1. The viewing direction from the

probe is parallel to the ecliptic plane and perpendicular to the sun (Fig. 2a); in the positive z direction (Fig. 2b); or parallel to the negative x direction (Fig. 2c). In all cases the models predict brightness values easily observable ($\geq 10 S_{10}$) at space probe z distances up to 0.4 A.U. (Model II) or up to approximately 1 A.U. (Models I and III), and at the same time observable differences between the models, particularly in the case of Model II with its flattened outer contours. Even if the density does not follow the functional forms we have chosen as examples, the brightness variation with space probe z distance at a constant observing direction will give a measure of the rate of dust decrease away from the ecliptic plane. To look for any systematic changes in the average scattering properties of the particles (size, composition) with z distance, polarization measurements as a function of elongation are necessary, in addition to brightness observations (see Giese and Dziembowski 1969).

Interstellar Dust

The existence of an interstellar component in the solar system dust cloud has been proposed by Greenberg (1969) and others. Even if such small particles are excluded from the inner solar system by radiation pressure, they might be observable with a sensitive detector at large heliocentric distance, during the

transfer orbit of an out-of-ecliptic probe. If we take, for example, a number density of $3 \cdot 10^{-13}$ particles/cm³ of interstellar origin and a relative velocity of 30 km/sec between the particles and a 100 cm² detector, 8 such particles should be detectable each day.

Conclusion

A joint dust experiment which combines direct detection of the velocity and mass of individual particles with measurements of the zodiacal light brightness and, if possible, polarization will best serve the purpose of an out-of-ecliptic mission.

These two complementary methods together will give a picture of the three-dimensional dynamics and spatial distribution of the interplanetary dust. Such a picture will help to clarify the relation of dust particles to cometary and asteroidal material as well as the interaction of the dust with the solar radiation field. The influence of the sun on particle motions and physical characteristics has a significance for the role of the dust in the early evolution of the solar nebula and early phases of stellar evolution.

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References

- Bedford, P. K., Proc. Roy. Soc. A 343, 277, 1975.
- Berg, O. E. and U. Gerloff, More than two years of micrometeorite data from two pioneer satellites, Space Res. XI, 225-235, 1971.
- Berg, O. E. and E. Grün, Evidence of hyperbolic cosmic dust particles, Space Res. XIII, 1047, 1973.
- Dietzel, H., G. Eichhorn, H. Fechtig, E. Grün, H. J. Hoffmann and J. Kissel, The HEOS 2 and HELIOS micrometeoroid experiments, Scientif. Instr. 6, 209-217, 1973.
- Dumont, R. and F. Sánchez-Martínez, Photométrie de la lumière zodiacale hors de l'ecliptique en quadrature et en opposition avec le soleil, Astron. and Astrophys. 22, 321-328, 1973.
- Dumont, R. and F. Sánchez-Martínez, Zodiacal light photometry, II gradients along the ecliptic and phase functions of interplanetary matter, Astron. and Astrophys. 38, 405-412, 1975.
- Fechtig, H., W. Gentner, J. B. Hartung, K. Nagel, G. Neukum, E. Schneider and D. Storzer, Microcraters on lunar samples, Soviet-American Conference on Cosmochemistry of the Moon and the Planets Moscow, 1974.
- Giese, R. H. and C. V. Dziembowski, Suggested zodiacal light measurements from space probes, Planet.Space Sci. 17, 949-956, 1969.

- Giese, R. H., Model computations concerning zodiacal light measurements by space probes, Space Res. XI, 255-260, 1971.
- Giese, R. H., Out-of-ecliptic dust, Eldo-Cecles/Esro-Cers Scient. and Techn. Rev. 7, 43-51, 1975.
- Greenberg, J. M., A possible interrelation between interstellar and interplanetary cosmic dust, Space Res. IX, 111-113, 1969.
- Grün, E., Personal communication 1975.
- Hanner, M. S. and C. Leinert, The zodiacal light as seen from the pioneer F/G and helios probes, Space Res. XII, 445-455, 1972.
- Hanner, M. S., J. G. Sparrow, J. L. Weinberg, D. E. Beeson, Pioneer 10 observations of zodiacal light brightness near the ecliptic: changes with heliocentric distance, IAU Colloquium No. 31, Heidelberg June 1975.
- Hemenway, C. L., D. S. Hallgreen and D. C. Schmalberger, Stardust, Nature 238, 256-260, 1972.
- Hoffmann, H. J., H. Fechtig, E. Grün, J. Kissel, First results of the micrometeoroid experiment S 215 on the HEOS 2 - satellite, Planet. Space Sci. 23, 215-224, 1975.
- Humes, D. H., J. M. Alvarez, W. H. Kinard and R. L. O'Neil, The interplanetary and near-Jupiter meteoroid environment, JGR 79, 3677-3684, 1974.
- Leinert, C., The zodiacal light - a measure of the interplanetary environment, Space Sci. Rev. (in print).

- Link, H., C. Leinert, E. Pitz, N. Salm, Preliminary results of the helios a zodiacal light experiment, IAU Colloquium No. 31, Heidelberg June 1975.
- Sekanina, Z., Modelling of the orbital evolution of vaporizing dust particles near the sun, IAU Colloquium No. 31, Heidelberg June 1975.
- Soberman, R. K., S. L. Neste and K. Lichtenfeld, Optical measurement of interplanetary particulates from pioneer 10, JGR 79, 3685-3694, 1974.
- Southworth, R. B. and Z. Sekanina, Physical and dynamical studies of meteors, NASA Contractor Rep. CR - 2316, 1973.
- Weinberg, J. I., The zodiacal light at 5300 \AA , Annales d'Astrophys. 27, No. 6, 718-738, 1964.
- Wyatt, S. P. and F. L. Whipple, The Poynting-Robertson effect on meteor orbits, Astrophys. J. 111, 134-141, 1950.
- Zook, H. A. and O. E. Berg, A source of hyperbolic dust particles, Plan. Space Sci. 23, 183-203, 1975.
- Zook, H. A., Hyperbolic cosmic dust: its origin and its astrophysical significance, Plan. Space Sci. (in press).

TABLE 1

	0°, 1 AU	30°, 1 AU			60°, 1 AU			90°, 1 AU		
		F	E	G	F	E	G	F	E	G
Spinner no sun p.	156	68	64	84	43	44	44	37	40	37
Spinner sun p.	156	119	117	125	108	109	109	106	107	106
3 Ax. Stab. Apex point.	120	53	49	64	33	34	34	29	31	29
3 Ax. Stab. sun point. no sun p.	300	132	122	161	83	84	85	72	76	72
3 Ax. Stab. sun point. sun p.	300	300	300	300	300	300	300	300	300	300

Numbers of events per orbit per year and per 100 cm² sensor surface
=====

F = Fan Model ($\gamma=2.9$)

E = Ellipsoid Model

G = Gauss Model

Figures

Fig. 1 Surfaces of equal number density of dust particles in the interplanetary cloud

n_0 number density in the ecliptic plane at 1 A.U.
from the sun

x solar distance in the ecliptic plane (A.U.)

z height above the ecliptic plane (A.U.)

a) Ellipsoid Model (ref. text case I, $\nu = 1$; $\gamma = 9$)

b) Gauss Model (case II; $\nu = 1$; $\gamma = 2.5$)

c) Fan Model (case III; $\nu = 1$; $\gamma = 3$).

Fig. 2 Brightness of the zodiacal light as seen by a spaceprobe ascending to an altitude of z (A.U.) above the ecliptic plane on a circular orbit of 1 A.U. radius.

S_{10} : Stars of 10th magnitude per square degree

dashed curve: Ellipsoid-model

dots : Gauss-model

solid curve : Fan-model

a) direction parallel to the ecliptic plane at right
angle to the solar direction ($\epsilon = 90^\circ$)

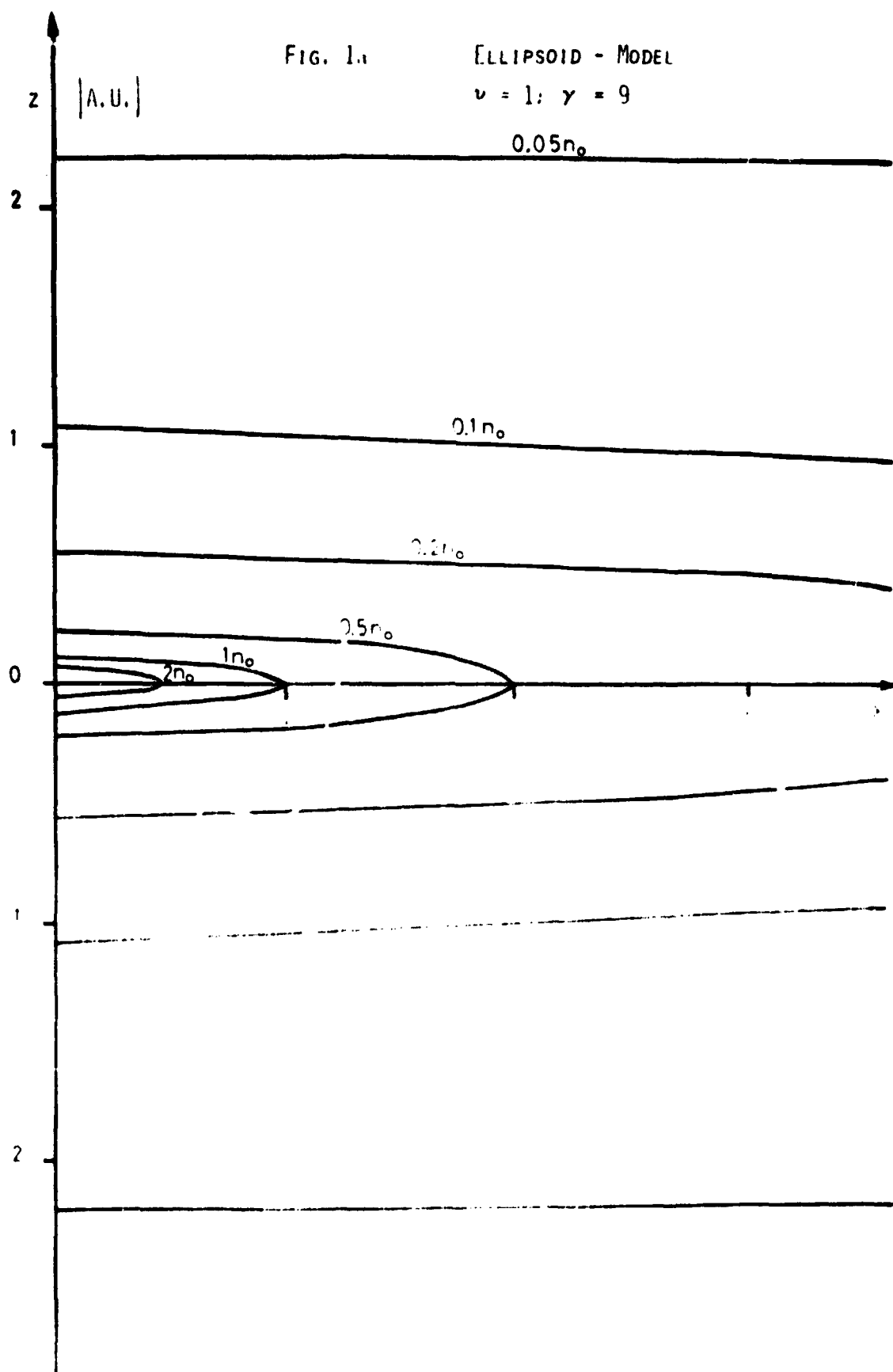
b) direction towards the ecliptic pole (+ z direction)

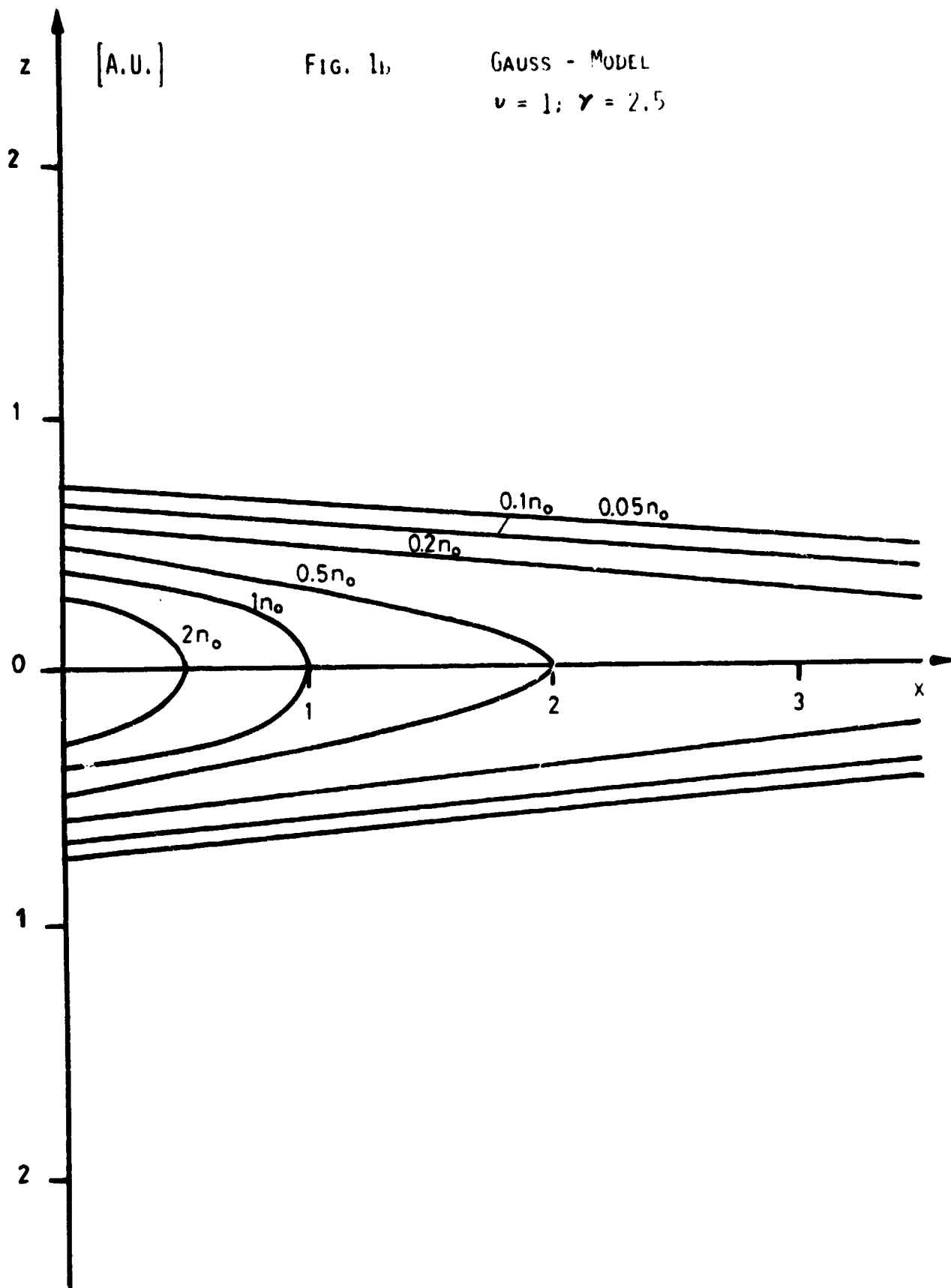
c) direction parallel to the ecliptic plane and
parallel to the earth-sun direction (- x axis).

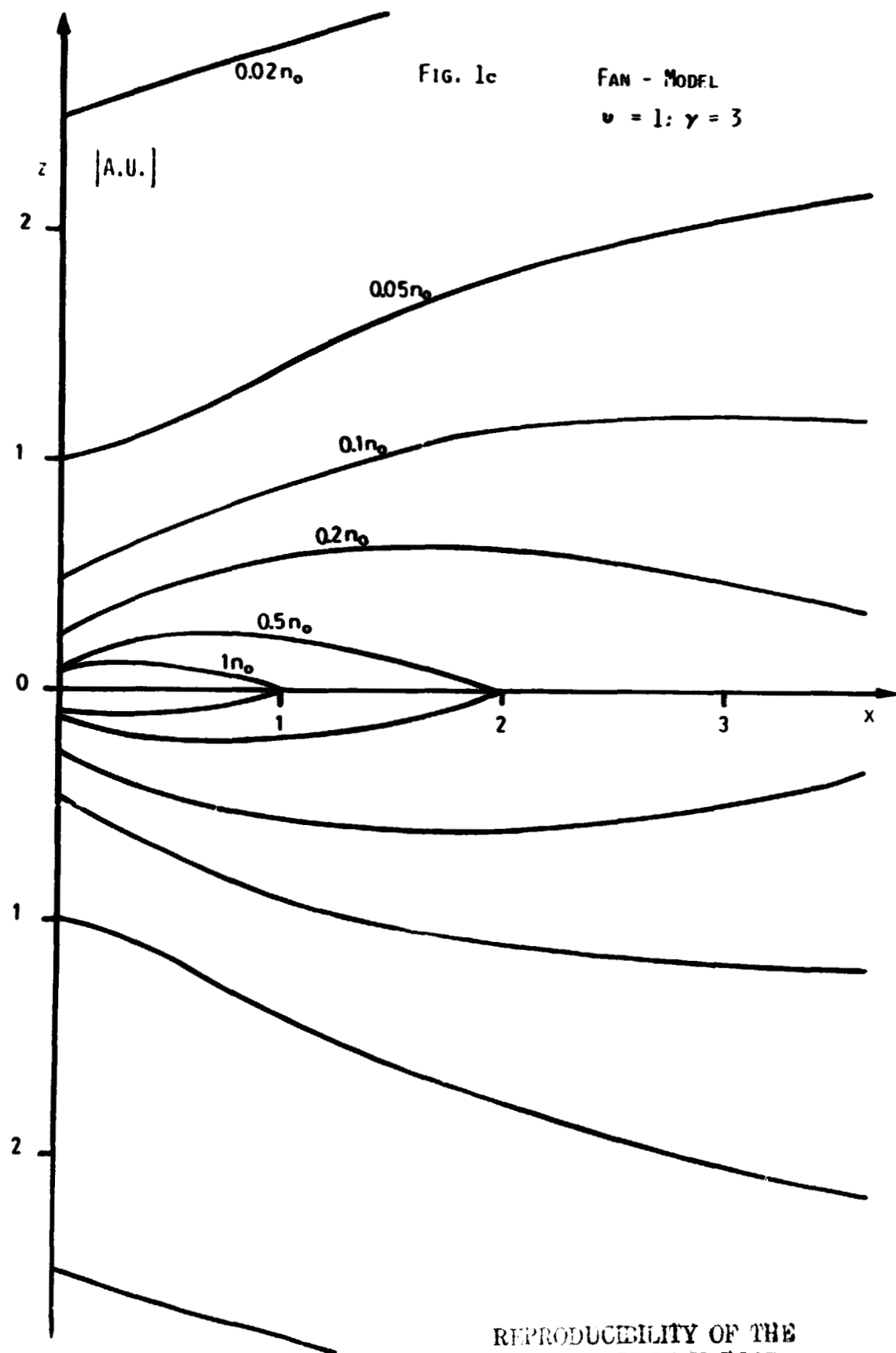
FIG. 1.1

ELLIPSOID - MODEL

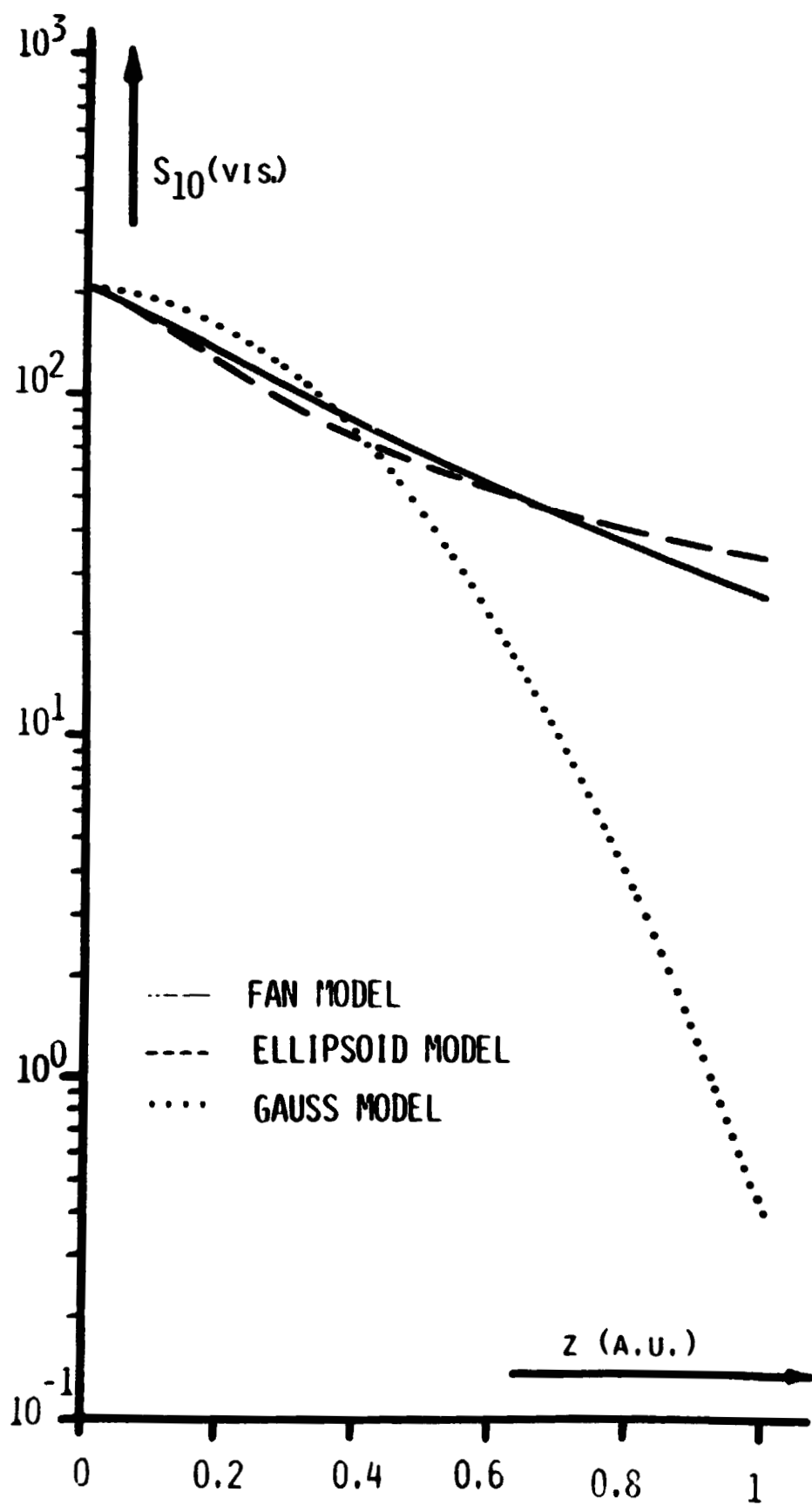
$\nu = 1; \gamma = 9$







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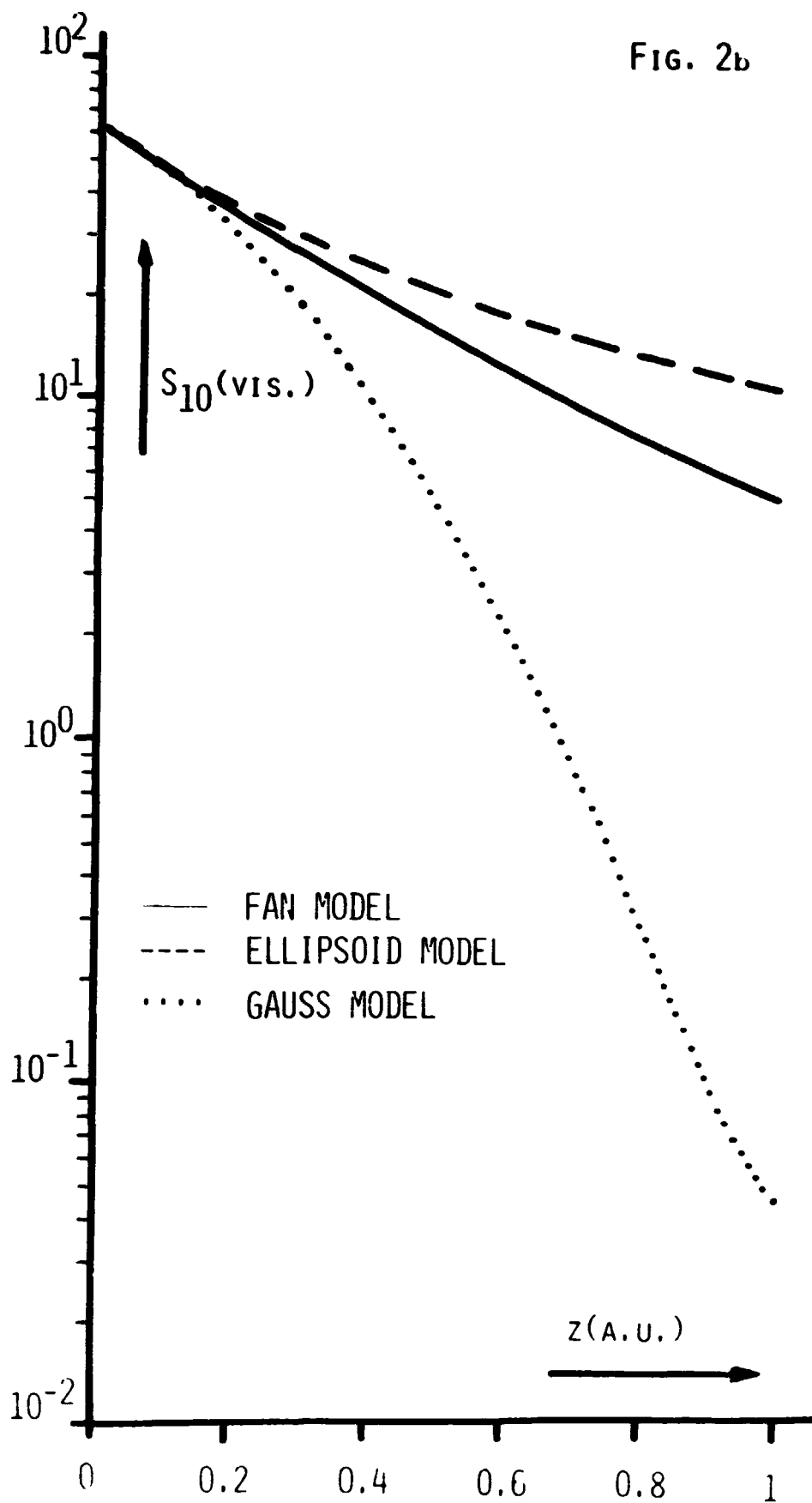


FIG. 2c

